Electroactive polymers (EAP) low mass muscle actuators

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ABSTRACT

Actuation devices are used for many space applications with an increasing need to reduce their size, mass, and power consumption as well as cut their cost. Existing transducing actuators, such as piezoceramics, induce limited displacement levels. Potentially, electroactive polymers (EAP) have the potential for low-mass, low-power, inexpensive miniature muscle actuators that are superior to the widely used actuators. Under electrical excitation, EAPs contract and thus form a basis for muscle actuators. Efforts are being made to develop EAP materials that provide large displacements, and two EAP categories were identified to produce actuation strain of more than 10%. These categories include: (a) ion-exchange membrane - platinum composite polymer (so-called ionomers); and (b) electrostatically driven polymers. A comparison between EAP and the widely used transducing actuators shows that, while lagging in force delivering capability, these materials are superior in mass, power consumption and displacement levels. This produces an enabling technology of a new class of devices. Several muscle configurations were constructed to demonstrate the capabilities of these EAP actuators. The emphasis of this manuscript is on ionomer actuators.

Keywords: actuators, electroactive polymers, active materials, ionomers

1. INTRODUCTION

Efficient miniature actuators that are light, compact and driven by low power are needed to support telerobotic requirements of future NASA missions. Generally, actuators are used to operate telerobotic devices that include robotic arms, rovers, etc. Other space applications include release mechanisms, antenna and instrument deployment, positioning devices, aperture opening and closing devices, and real-time compensation for thermal expansion in space structures, etc. Increasingly, there are requirements to reduce the size, mass, and power consumption of actuation devices, as well as their cost. Electroceramics (piezoelectric and electrostrictive) offer effective, compact, actuation materials that replace electromagnetic motors. A wide variety of Electroactive ceramics (EAC) materials are incorporated into motors, translators and manipulators, in such devices as ultrasonic motors and inchworms. In contrast to electroceramics, EAPs are emerging as new actuation materials [1] with displacement capabilities that cannot be matched by the striction-limited and rigid ceramics. Table 1 shows a comparison between the capability of EAP materials to electroceramics and shape memory alloys. As shown in Table 1, EAP materials are lighter and their potential striction capability can be as high as two orders of magnitude more than EAC materials. Further, their response time is significantly higher than shape memory alloys (SMA). The authors' current study is directed towards taking advantage of these polymers' resilience and the ability to engineer their properties to meet telerobotic articulation requirements. The mass producibility of polymers and the fact that electroactive polymer materials do not require poling (in contrast to piezoelectric materials) help in producing them at low cost. EAP materials can be easily formed in any desired shape and can be used to build micro-electro-mechanical-type mechanisms (actuators and sensors). They can be designed to emulate the operation of biological muscles [2-5] and they have unique characteristics of low density as well as high toughness, large actuation strain constant and inherent vibration damping.

TABLE 1: Comparison of the properties of EAP, SMA and EAC

Property	Electroactive polymers (EAP)	Shape memory alloys (SMA)	Electroactive Ceramics (EAC)
Actuation displacement	>10%	<8% short fatigue life	0.1 - 0.3 %
Force (MPa)	0.1 - 3	about 700	30-40
Reaction speed	μsec to sec	sec to min	μsec to sec
Density	1- 2.5 g/cc	5 - 6 g/cc	6-8 g/cc
Drive voltage	4 - 7 V	NA	50 - 800 V
Power consumption	m-watts	watts	watts
Fracture toughness	resilient, elastic	elastic	fragile

2. DEVELOPMENT OF MUSCLE ACTUATORS

The development of muscle actuators is based on an interdisciplinary effort using expertise in materials science, chemistry, electronics, and robotics. The initial effort concentrated on identifying EAP with 10% actuation strain. This goal was set in reference to the capability of SMAs that induce 8% maximum striction (at a relatively short fatigue life of 1K-cycle). Compared to EACs, which produce a fraction of a percent actuation, SMAs produce a relatively large displacement and they are increasingly being considered for space applications (e.g., pin-pullers). Two categories of EAP actuators were investigated, including (a) Perfluorinated ion-exchange membrane platinum (PIEP) composites, and (b) Linear EAP actuators - employing electrostatically activated EAPs. The emphasis of the current study is on the PIEP composites category, which displays a strong bending capability.

The PIEP muscle is composed of a perfluorinated ion exchange membrane (IEM), with chemically deposited platinum electrodes on its both sides. The thickness of the formed muscle actuator is 0.18-mm and it is cut in strips that are 1x0.125-inch in area and weighs 0.1 gram. To maintain their actuation capability the films need to be kept moist continuously. The commercially available IEM has the following chemical formula,

$$[-(CF_2\text{-}CF_2)_n\text{-}CF\text{-}CF_2\text{-}]_m$$
$$|$$
$$O\text{-}CF\text{-}CF_2\text{-}O\text{-}CF_2\text{-}SO_3\text{-}M$$
$$|$$
$$CF_3$$

where $n \sim 6.5$, $100 < m < 1000$, and M^+ is the counter ion (H^+, Li^+ or Na^+). The structure and properties of the IEM have been the subject of numerous investigations (see for example [6-10]). One of the interesting properties of this material is its ability to absorb large amounts of polar solvents, i.e. water. In order to chemically electrode the PIEP, platinum (Pt) metal ions are dispersed throughout the hydrophilic regions of the polymer, and are subsequently reduced to the corresponding zero valent metal atoms. This results-in the formation of a dendritic type electrodes. In Figure 1, a scanning electron micrographs are shown in two magnifications. On the left, a view is shown of the edge of an electroded PIEP composite muscle, the Pt metal covers each surface of the film with some of the metal penetrating the subsurface regions of the material. A closer view with x10 magnification is shown in Figure 1 on the right.

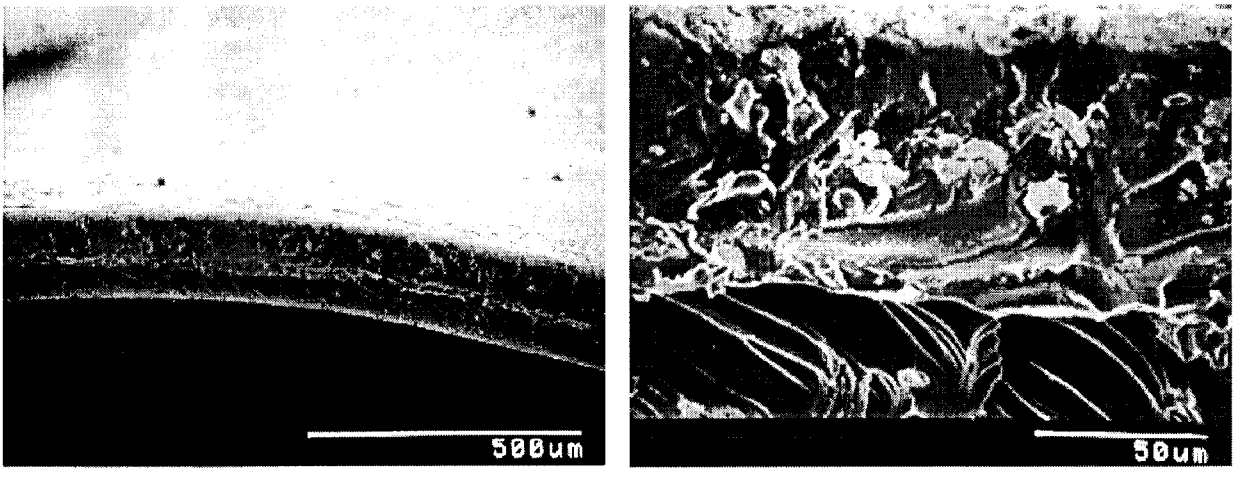

Figure 1: Scanning electron micrographs of the structure of PEIP composite film

When equilibrated with aqueous solutions these membranes are swollen and they contain a certain amount of water. Swelling equilibrium results from the balance between the elastic forces of the polymeric matrix and the water affinity to the fixed ion-exchanging sites and the moving counter ions. The water content depends on the hydrophilic properties of the ionic species inside the membrane and also on the electrolyte concentration of the external solution.

When an external voltage of 2 volts or higher is applied on a PIEP composite film, it bends towards the anode. An increase in voltage level (up to 6 or 7 volts) causes a larger bending displacement. An alternating voltage is applied, the film undergoes movement like a swing and the displacement level depends not only on the voltage magnitude but also on the frequency. Lower frequencies (down to 0.1 or 0.01 Hz) lead to higher displacement (approaching 1 inch). Thus, the movement of the muscle is fully controllable by the applied electrical source. The muscle performance is also strongly dependent on the water content which serves as an ion transport medium. The frequency dependence of the ionomer deflection as a function of the applied voltage is shown in figure 2. A single film was used to simulate a miniature bending arm that lifted a mass weighing a fraction of a gram. A film-pair weighing 0.2-g was configured as a linear actuator and using 5V and 20 mW successfully induced more than 11% contraction displacement. Also, the film-pair displayed a significant expansion capability, where a stack of two film-pairs 0.2-cm thick expanded to about 2.5 cm wide (see Figure 3).

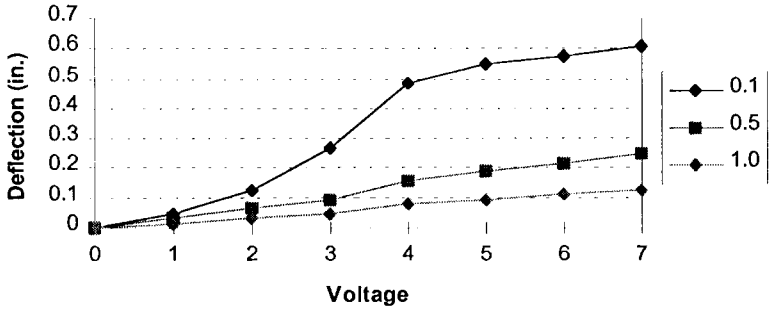

Figure 2: The deflection of a PIEP composite film as a function of the frequency and the applied voltage. The three curves represent the deflection as a function of frequency (Hz).

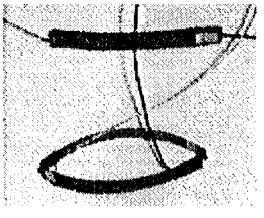

Figure 3: PIEP composite film-pair in expanded mode. A reference pair (top) and an activated pair (bottom).

3. MUSCLE ACTUATOR FOR ROBOTIC APPLICATIONS

PIEP composite films have shown remarkable displacement under a relatively low voltage drive, using a very low power. However these ionomers have demonstrated a relatively low force actuation capability. Since the PIEP composite films are made of a relatively strong material with a large displacement capability, we investigated their application to simulate fingers. In Figure 4, a gripper is shown that uses PIEP composite fingers in the form of an end-effector of a miniature low mass robotic arm.

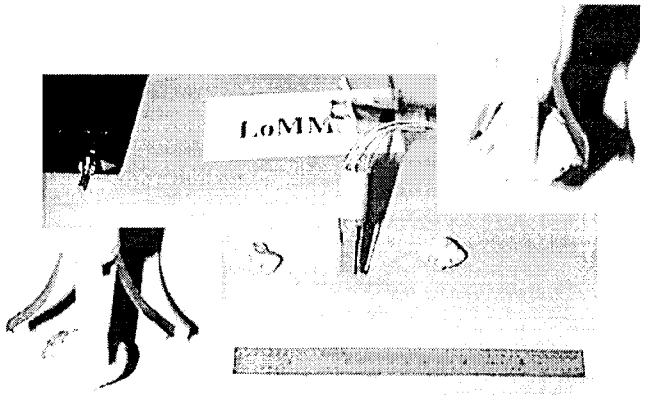

Figure 4: An end-effector gripper lifting 10.3-g rock under 5-V, 25-mW activation using four 0.1-g fingers made of perfluorinated ion-exchange membrane platinum composite.

The fingers are shown as vertical gray bars and the electrical wiring, where the films are connected back-to-back, can be seen in the middle portion of Figure 4. Upon electrical activation, this wiring configuration allows the fingers to bend either inward or outward similar to the operation of a hand and thus close or open the gripper fingers as desired. The hooks at the end of the fingers are representing the concept of nails which secure the gripped object that is encircled by the fingers.

So-far, multi-finger grippers that consist of 2- and 4-fingers were produced, where the 4-finger gripper lifted a mass of 10.3-g (shown in Figure 4). This gripper prototype was mounted on a 5-mm diameter graphite/epoxy composite rod to simulate a light weight robotic arm. This gripper was driven by 5 volts square wave signal at a frequency of 0.1 Hz to allow sufficient time to perform a desirable demonstration of the capability of the gripper -- opening the gripper fingers, bringing the gripper near the collected object, closing the fingers and lifting an object with the arm. The demonstration of this gripper capability to lift a rock was intended to pave the way for a future application of the gripper to planetary sample collection tasks (such as Mars) using ultra-dexterous and versatile end-effector.

To enhance the force actuation capability of PIEP composite actuators, techniques for producing thicker PIEP films are being developed. Further, we are seeking a better understanding of the actuation mechanism of ionomers as well as searching alternatives ionomer actuators. Also, to protect the ionic constituents of PIEP composite films, encapsulation methods are being developed..

4. CONCLUSIONS

A new type EAP actuator based on an innovative processing of PIEP composite films was developed. This electroactive polymer, PIEP composite, is superior in actuation displacement over the traditional actuators. This superior capability is compared to conventional electromagnetic actuators as well as the transducing types, such as piezoceramics and shape memory alloys. This superiority of PIEP composites is defined in terms of mass, cost and

power consumption. While the force actuation capability is limited, its displacement level is unmatched. Multifinger grippers were demonstrated to have a large fingers opening and closing displacement and a great mass carrying capability. The construction of a robotic arm with a PIEP composite gripper end-effectors is underway and appears promising for future space missions. The material requires maintenance of the ionic constituents that are responsible for the bending effect. These ions are contained in the moist PIEP composite films and encapsulation techniques are currently being investigated to assure their containment.

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